Coal Operators' Conference

Faculty of Engineering and Information Sciences

2-2017

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Recommended Citation

Dennis Black, Control and management of gas emissions to reduce production delays and fugitive emissions, in Naj Aziz and Bob Kininmonth (eds.), Proceedings of the 2017 Coal Operators' Conference, Mining Engineering, University of Wollongong, 18-20 February 2019
https://ro.uow.edu.au/coal/679

CONTROL AND MANAGEMENT OF GAS EMISSIONS TO REDUCE PRODUCTION DELAYS AND FUGITIVE EMISSIONS

Dennis Black[1,2]

ABSTRACT: The process of longwall coal extraction coal causes fractures in the overlying and underlying strata and these fractures become pathways for gas released from adjacent coal seams to flow into the mine workings and contaminate the ventilation air. If the rate of gas emission exceeds the diluting capacity of the ventilation air, the gas concentration will increase and exceed the statutory limit resulting in production delays.

All potential gas sources within the planned mining area, including coal seams located above and below the working seam, should be identified and sufficient gas data collected and used to determine the specific gas emission from each gas source. Gas reservoir and emission modelling is recommended to determine specific gas emission and changes in gas emission from individual sources over the planned mining area. Accurate gas reservoir and emission modelling provides the information required to accurately design gas drainage programs to effectively manage gas emissions and minimise the risk of 'gas-outs'.

INTRODUCTION

To effectively control and manage gas emissions in an underground coal mine, sufficient information must be collected to enable all potential gas emission sources to be identified. Each potential source should be investigated to determine the volume and rate of gas release during mining operations. There are many potential sources of gas emission in an underground coal mine (Black and Aziz, 2009), as indicated in Figure 1, which includes:

A. Emission from exposed mine roadways;
B. Emission during coal cutting – both development and longwall;
C. Emission into longwall goaf from adjacent gas bearing coal seams and strata;
D. Emission from longwall goaf into connecting airways; and
E. Emission from coal being transported from mine via the coal clearance system.

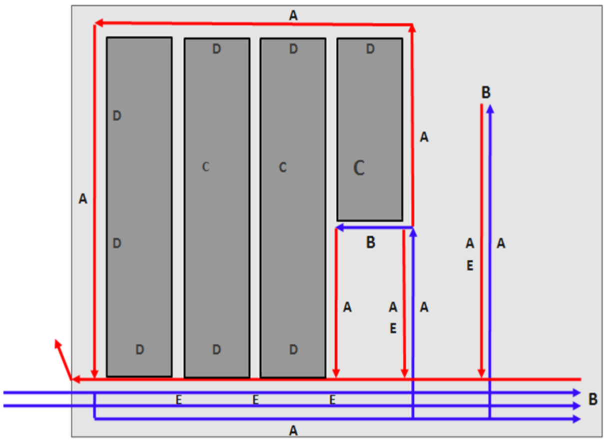

Figure 1: Sources of gas emission in a typical underground longwall coal mine

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Mine operators are required to maintain a safe workplace and provide safety management systems which include provisions to maintain gas concentrations within all accessible places within the mine below prescribed statutory limits (WHS Regulation, 2014). In cases where the mine has not identified and assessed all potential gas sources and insufficient capacity has been provided in the ventilation and gas management systems, the risk of exceeding the statutory gas concentration limits is greatly increased.

Incorporating gas reservoir analysis and gas emission forecasting into the mine planning process provides a means of forecasting the return airway gas concentration for periods defined in the mine production schedule. This process allows the impact on gas concentration, from varying the level of pre-drainage and goaf drainage, to be assessed.

The steps from initial exploration data collection through to forecasting the return airway gas concentration, including pre-drainage to reduce the specific gas emission and goaf drainage to reduce the volume of gas released into the longwall ventilation system, are listed below:

- Exploration (Data Collection)
- Gas Reservoir Modelling
- Specific Gas Emission Calculations
    - Specific gas emission is effected by mine design i.e. longwall face width and cut height
    - Pre-drainage may be used to reduce specific gas emission
- Longwall Gas Make Calculations
    - Longwall gas make is effected by production rate i.e. high production equals high gas make
- Return Airway Gas Concentration
    - Gas emissions and return airway gas concentration is effected by goaf gas extraction rate i.e. removing gas from the goaf prior to being released into the mine ventilation system;
    - Ventilation air quantity dilutes gas emissions therefore has some effect on reducing return airway gas concentration.

EXPLORATION DRILLING AND DATA ACQUISITION

Data collection during exploration programmes has a significant impact on determining the size and significance of the gas reservoir, and identifying specific areas and coal seams that may require gas drainage as a pre-emptive action to reduce gas emissions when the area is mined.

Quite often exploration tends to focus on the working seam and little information is collected from coal seams and other gas bearing strata that may be present above and below the working seam. Although exploration drilling will pass through coal seams above the working seam, core samples are not regularly collected for gas testing and proximate analysis, and logging may not accurately pick the level to the top and base of each coal seam. It is also quite common that the total depth of exploration boreholes will not extend further than approximately ten metres below the base of the working seam. In areas where coal seams are present below the working seam, the absence of exploration data prevents accurate assessment of the impact of gas emissions during longwall extraction. In areas where coal seams may be present below the working seam, it is recommended that exploration boreholes extend approximately 40-50 metres below the target working seam and the depth and thickness of all coal seams in the sequence are identified and recorded.

Figure 2 illustrates the difference between two exploration boreholes; (A) the total depth of the borehole extends approximately 80 metres below the base of the working seam (D seam) and all coal seams have been accurately logged, and (B) the total depth of the borehole extends less than ten metres below the base of the working seam, no information has been collected to allow an assessment of gas emission potential from underlying coal seams and limited detail is available from overlying coal seams.

Table 1 lists gas reservoir data collected from exploration borehole BH223, which includes data collected from five coal seams above, and five seams below, the D seam.

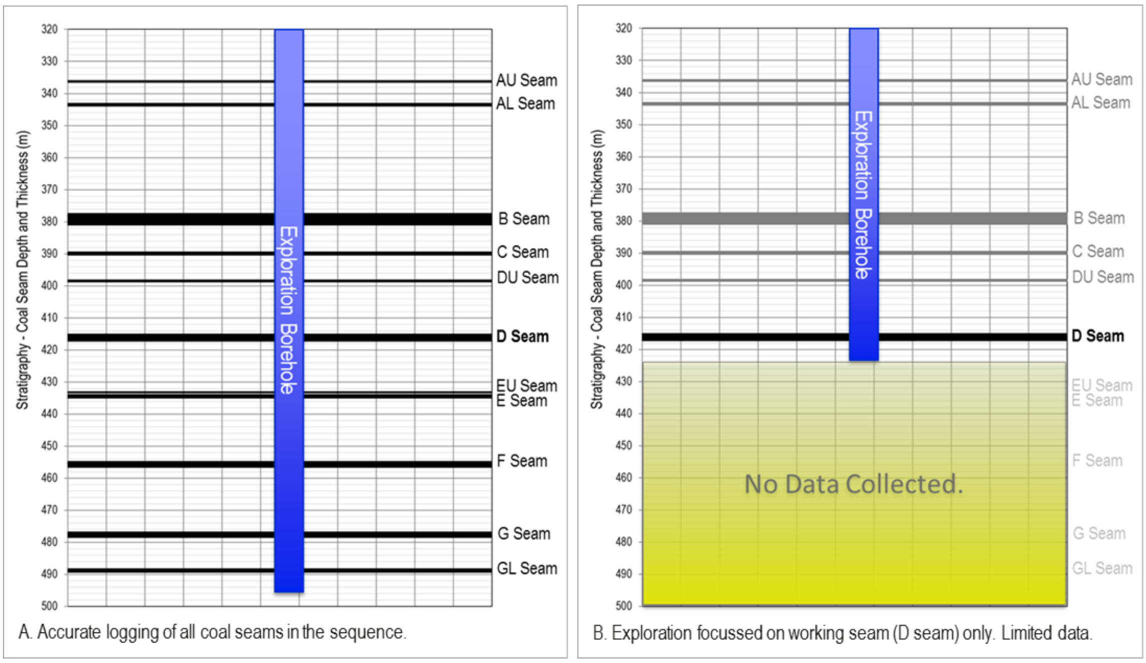

Figure 2: Use of exploration drilling to accurately identify and collect data from coal seams with gas emission potential

Table 1: Gas reservoir information collected from exploration borehole BH223

GAS BEARING STRATA		Depth to Seam Roof (m)	Depth to Seam Floor (m)	Seam Thickness (m)	RD (t/m^3)	Gas Comp. $\%CH_4$	Distance Above/Below Working Seam (m)	Virgin Gas Content (m^3/t)
ROOF SEAMS	A Upper Seam	335.90	336.62	0.72	1.44	100	78.5	4.37
	A Lower Seam	342.69	344.23	1.54	1.30	100	70.9	4.50
	B Seam	377.16	381.20	4.04	1.38	100	33.9	5.15
	C Seam	389.49	390.38	0.89	1.30	100	24.7	5.87
	D Upper Seam	398.12	398.90	0.78	1.32	100	16.2	6.02
	D Seam	415.08	417.20	2.12	1.31	100		7.30
FLOOR SEAMS	E Upper Seam	432.73	433.73	1.00	1.38	100	15.5	7.50
	E Seam	433.73	435.12	1.39	1.37	100	16.5	7.61
	F Seam	454.17	457.34	3.17	1.32	100	37.0	7.48
	G Seam	476.41	478.89	2.48	1.27	100	59.2	7.89
	G Lower Seam	488.21	489.54	1.33	1.35	100	71.0	8.03

The number of exploration boreholes planned to be drilled in an exploration programme should cover the planned mining area and the spacing between boreholes should be close enough to identify changes in reservoir characteristics. In cases where unexpected and unusual results are obtained from an exploration borehole, additional drilling should be planned near that borehole to check the accuracy of the previous results and collect additional data to assist in detailing the changes to the gas reservoir in those areas.

Figure 3 shows the location of twenty-two (22) exploration boreholes drilled over a planned longwall mining area. In this example, no exploration boreholes have been drilled over the final four (4) longwall panels. The layout of most longwall mines is such that mining commences in relatively shallow conditions and, during the mine life, mining depth and the gas content of the coal seam tends to increase. It is important that exploration drilling and data collection is completed well ahead of planned mining and provides sufficient time to (a) assess the gas reservoir, and (b) design and implement effective gas management and emission reduction measures to control forecast gas emissions.

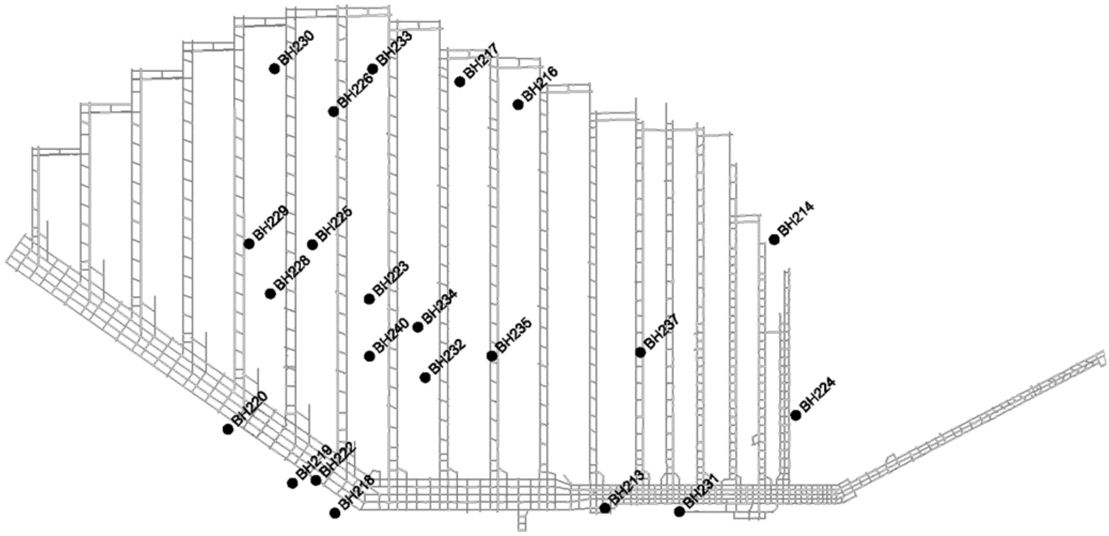

Figure 3: Location of exploration boreholes covering the planned longwall mining area

GAS RESERVOIR ANALYSIS

Analysis of the gas reservoir is recommended to identify the relative impact of all potential sources of gas emission within the goaf and to evaluate the impact of pre-drainage to remove gas from specific coal seams to reduce total Specific Gas Emission (SGE), prior to longwall extraction.

Accurate analysis of the gas reservoir requires a comprehensive record of results from gas testing and proximate analysis of coal samples collected from all coal seams intersected during drilling of a sufficiently large number of exploration boreholes covering the planned mining area. In cases where reservoir data is not available for specific coal seams and/or the spacing between exploration boreholes is too great, the accuracy of the gas reservoir analysis decreases due to reliance on interpolation between known data points.

The total SGE (m^3/t) is calculated at each exploration reference borehole location and requires the addition of SGE values calculated for each coal seam located above and below the working section that will release gas into the goaf following longwall extraction. In addition to the reservoir information listed in Table 1 and details of the width and height of the mining excavation, the caving angles above and below the working seam are used to calculate the degree of gas emission (%) from each of the overlying and underlying coal seams. In this example, the Flugge Goaf Caving Model (MEA, 2006), is used to calculate the degree of emission. The equation presented below, Equation 1, incorporates the Flugge degree of emission calculation (MEA, 2006), and is presented as the method to calculate the SGE contribution (m^3/t) from individual coal seams. The total SGE at each reference borehole location is calculated by adding the SGE contributions from each coal seam in the sequence.

$$SGE_i = \frac{((Q_M - Q_D - Q_R) \times H_i \times RD_i) \times \left(\left(\left(D_{LW} - (2 \times d_i \div \tan\beta)\right) \times 100\right) \div D_{LW}\right)}{(H_{LW} \times RD_{LW})}$$

Where:

Q_M is the measured virgin coal seam gas content;

Q_D is the gas content reduction by gas drainage;

Q_R is the residual gas content of the coal seam, post longwall extraction;
H_i is the thickness of the coal seam;
RD_i is the relative density of the coal seam;
D_{LW} is the width of the longwall face;
d_i is the distance of the coal seam above/below the working seam section;
β is the caving angle of the longwall goaf above/below the working seam section;
H_{LW} is the height of the working seam section; and
RD_{LW} is the relative density of the working seam.

Figure 4 shows the gas content and SGE contribution of each coal seam intersected by borehole BH223. In this example, there has been no pre-drainage to reduce gas content below virgin levels, and the total SGE is 20.5 m^3/t. The greatest individual SGE contributions are from D seam (6.5 m^3/t) and B seam (5.2 m^3/t). Figure 4 also shows that if no data was collected below the D seam, the SGE would be incorrectly calculated at 15.1 m^3/t.

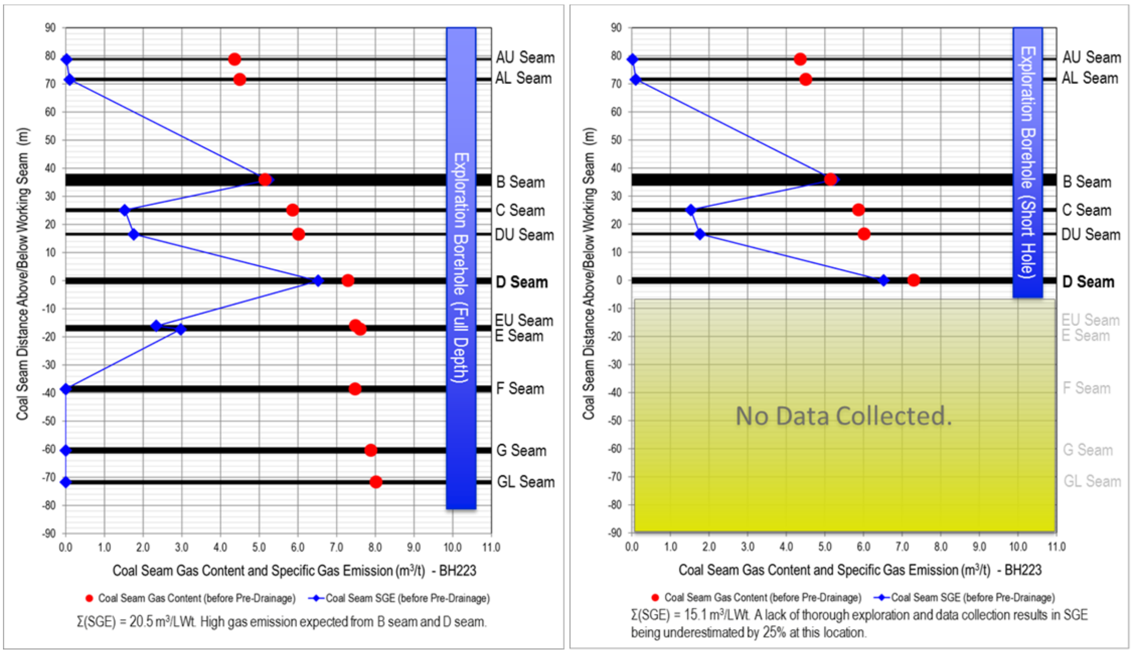

Figure 4: SGE contribution by coal seam with no pre-drainage to reduce gas emissions from individual coal seams

Figure 5 shows contours of the total SGE expected when mining each longwall panel and these values are based on no pre-drainage to reduce gas content prior to mining. Underground coal mines will typically commence pre-draining the working seam in areas where the gas content is above 5.0 to 6.0 m^3/t. There may be a number of factors that necessitate the use of pre-drainage which may include (a) reducing rib emissions to maintain the gas concentration of intake ventilation air below 0.25% CH_4, (b) reducing the gas content of the working seam below defined outburst threshold gas content limits, and (c) reducing the gas content of the working seam to avoid high gas emissions during the coal cutting cycle that may deenergise the cutter head and face equipment due to gas concentrations exceeding prescribed maximum concentrations. The results presented in Figure 4 show relatively high SGE from both B and D seams therefore the impact of pre-drainage to reduce the gas content of these two seams should be considered.

Figure 6 shows the impact of pre-draining the B seam to 4.0 m^3/t and the D seam to 3.0 m^3/t which achieves a 30% reduction in SGE at borehole BH223, reducing the SGE from 20.5 m^3/t to 14.2 m^3/t. The reduction on total SGE, achieved through pre-draining the D seam and parts of the B seam, is shown in Figure 7.

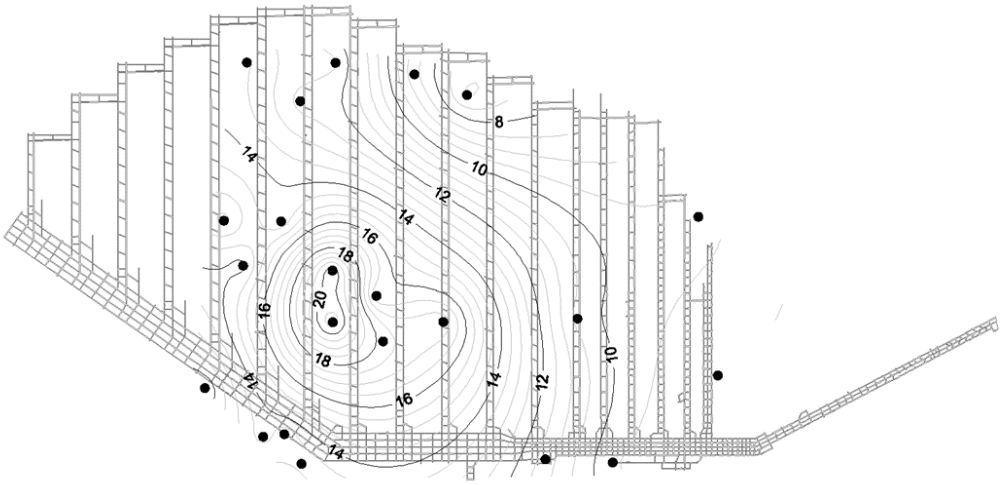

Figure 5: Specific Gas Emission (m^3/t) with no pre-drainage to reduce total gas-in-place and emissions from individual coal seams

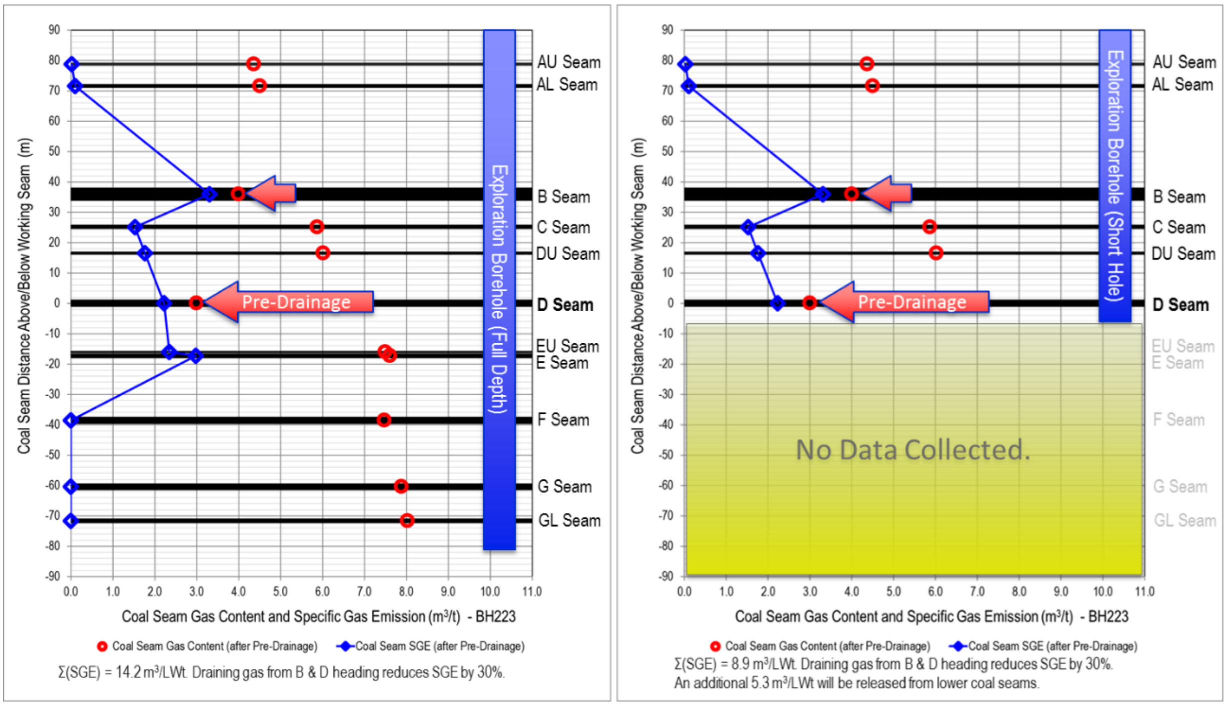

Figure 6: SGE contribution by coal seam after pre-draining B seam to 4.0 m^3/t and D seam to 3.0 m^3/t

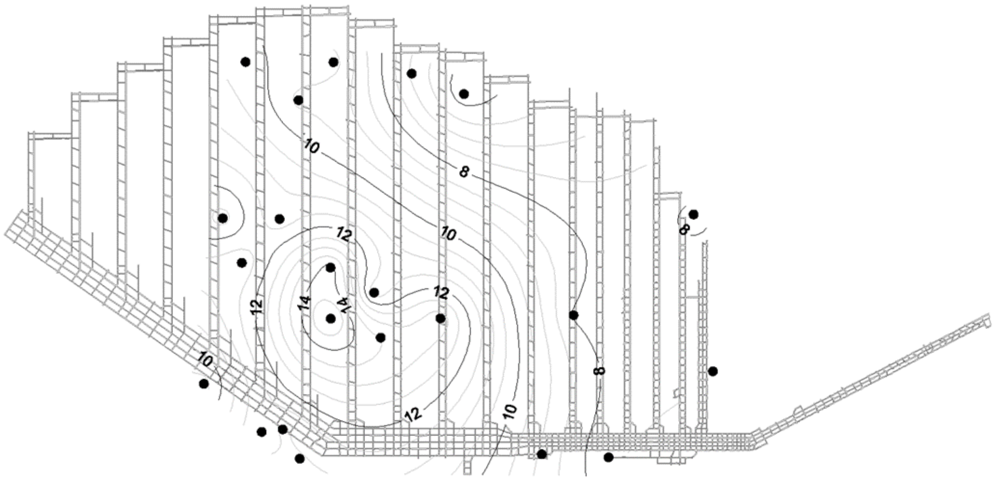

Figure 7: Specific Gas Emission (m^3/t) after pre-draining B seam to 4.0 m^3/t and D seam to 3.0 m^3/t

Details of the gas reservoir data and emissions calculated for each coal seam intersected by borehole BH223 are listed in Table 2.

Table 2: Gas reservoir information and gas emission calculation results for exploration borehole BH223

GAS BEARING STRATA		Depth to Seam Roof (m)	Depth to Seam Floor (m)	Seam Thickness (m)	RD (t/m^3)	Gas Comp. %CH_4	Distance Above/Below Working Seam (m)	Virgin Gas Content (m^3/t)	Gas Drained Pre-Mining (m^3/t)	Residual Gas Content (m^3/t)	Potential Gas Emission (m^3/t)	Mass of Coal in Seam (t/m^2)	Potential Gas Emission (m^3/m^2)	Degree of Gas Emission (%)	Specific Gas Emission (m^3/t)
ROOF SEAMS	A Upper Seam	335.90	336.62	0.72	1.44	100	78.5	4.37		4.30	0.07	1.04	0.07	62.29	0.02
	A Lower Seam	342.69	344.23	1.54	1.30	100	70.9	4.50		4.30	0.21	2.00	0.41	65.94	0.10
	B Seam	377.16	381.20	4.04	1.38	100	33.9	5.15	1.2	2.02	1.98	5.56	10.99	83.71	3.31
	C Seam	389.49	390.38	0.89	1.30	100	24.7	5.87		1.71	4.16	1.15	4.81	88.13	1.52
	D Upper Seam	398.12	398.90	0.78	1.32	100	16.2	6.02		0.85	5.17	1.03	5.31	92.22	1.76
	D Seam	415.08	417.20	2.12	1.31	100		7.30	4.3	0.78	2.22	2.78	6.18	100.00	2.22
FLOOR SEAMS	E Upper Seam	432.73	433.73	1.00	1.38	100	15.5	7.50		0.80	6.69	1.38	9.21	70.73	2.34
	E Seam	433.73	435.12	1.39	1.37	100	16.5	7.61		1.31	6.30	1.91	12.01	68.85	2.97
	F Seam	454.17	457.34	3.17	1.32	100	37.0	7.48		7.48	0.00	4.19	0.00	30.32	0.00
	G Seam	476.41	478.89	2.48	1.27	100	59.2	7.89		7.89	0.00	3.15	0.00	0.00	0.00
	G Lower Seam	488.21	489.54	1.33	1.35	100	71.0	8.03		8.03	0.00	1.79	0.00	0.00	0.00
TOTAL SPECIFIC GAS EMISSION		m^3 gas per tonne of coal produced													14.24
		litres gas per tonnes of coal produced													14,240

PRE-DRAINAGE

Figure 8 shows the level of gas content reduction required from pre-drainage to reduce the gas content of the D seam from virgin levels to the 3.0 m^3/t pre-mining gas content target. In this example, the B seam has also been identified as a target for pre-drainage with a target to reduce the gas content to below 4.0 m^3/t. The virgin gas content of the B seam is presented in Figure 9 and the contours show that, up to the limit of current exploration data, there is a relatively small area where gas content exceeds 4.0 m^3/t therefore only a small area requires pre-drainage.

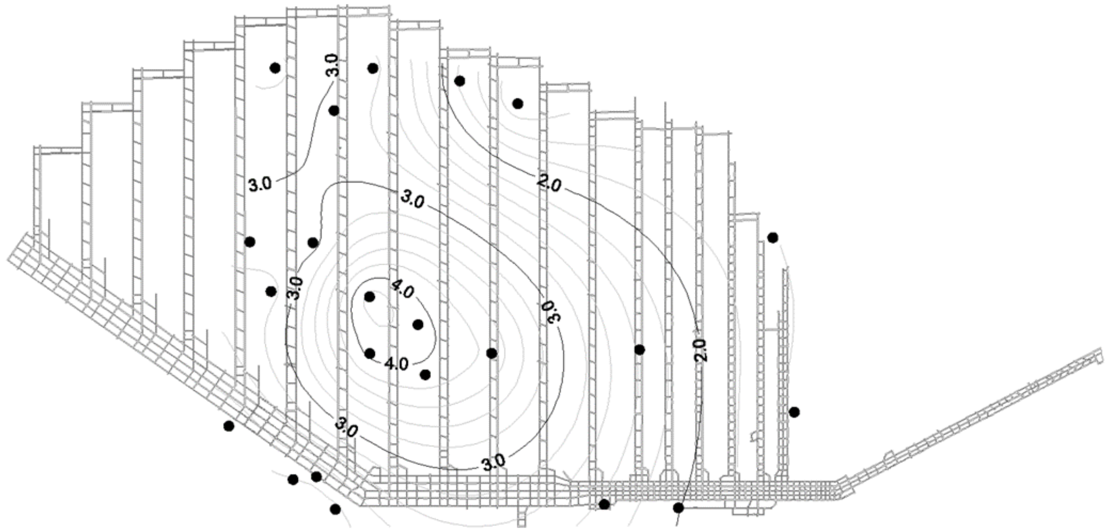

Figure 8: Gas content (m^3/t) to be removed from D seam by pre-drainage to achieve the target 3.0 m^3/t pre-mining gas content

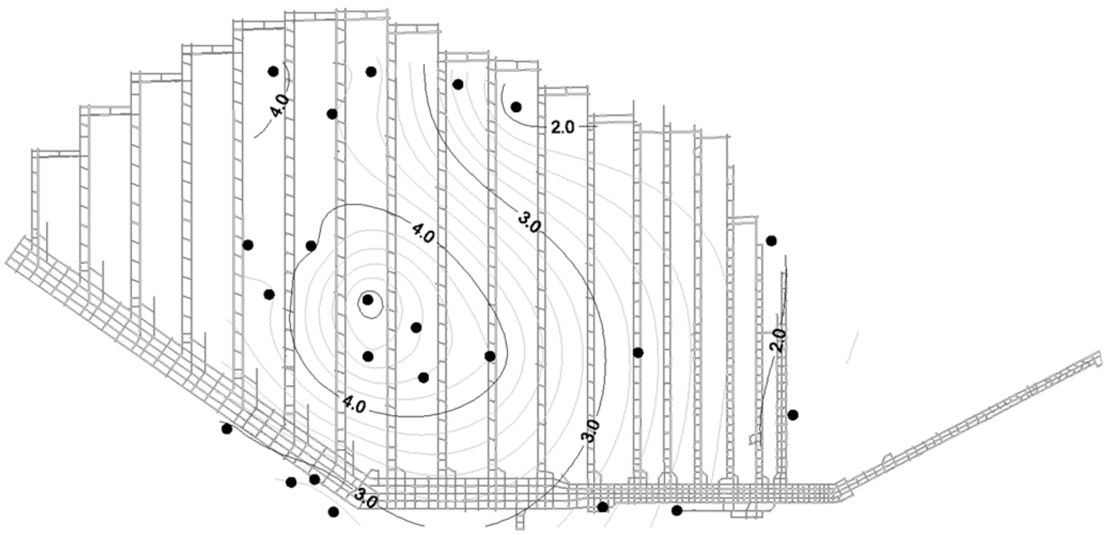

Figure 9: Gas content of the B seam (m^3/t) – contours indicate areas greater than 4.0 m^3/t that require pre-drainage

Drilling boreholes into coal seams to pre-drain gas prior to mining is achieved by (a) surface drilling methods, commonly referred to as Surface-to-Inseam (SIS) drilling, (b) underground drilling methods, commonly referred to as Underground-to-Inseam (UIS) drilling, or (c) a combination of both SIS and UIS drilling methods (Black and Aziz, 2009). Compared to UIS drilling, SIS is high cost and to achieve a reasonable return on investment, it is necessary to drill SIS boreholes many years ahead of planned mining to provide a minimum 3 to 5 year drainage time. In comparison, UIS boreholes typically have a short life and provide drainage for 6 to 12 months. Therefore, UIS gas drainage requires a greater number of closely spaced boreholes to achieve effective gas content reduction over the short drainage period.

Often, a combination of SIS and UIS drilling will be used, SIS initially to drain gas from areas that are beyond the reach of UIS drilling, followed by UIS to drain areas where the gas content remains greater than the target pre-mining gas content threshold levels. In addition to drainage time and drilling cost, there are many factors, such as those listed in Table 3 that should be considered during the process of selecting a drilling method(s) to effectively and efficiently pre-drain gas from a coal seam (Black and Aziz, 2010). The gas drainage characteristics specific to the coal seam to be drained should be understood and the gas drainage program designed to achieve maximum gas drainage efficiency (Black and Aziz, 2011).

Table 3: Factors to be considered in the selection of pre-drainage drilling method and drilling patterns

Gas content	Gas content reduction required by pre-drainage
Gas composition	Mining schedule and available drainage time
Degree of saturation	Area to be drained and distance from existing mine workings
Permeability	Potential changes and uncertainty of the mine plan
Seam thickness	Depth to target coal seam
Seam dip	Geological structures
Cleat and stress orientation	Surface access for drilling and gas management infrastructure
Coal type and rank	Underground access for drilling and gas management infrastructure

GAS EMISSION ANALYSIS

The gas emission rate is a measure of the volume of gas that will be released from the combined gas sources during coal production operations at the mine. The average gas emission rate in this example is calculated based on an average production rate of 1,000 tonnes per hour. Average annual production is 4.0 Mtpa, there are 50 planned production weeks per year, and 80 production hours per week. The average longwall gas make resulting from an average production rate of 1,000 tonnes per operating hour, having pre-drained the B and D seam to 4.0 m^3/t and 3.0 m^3/t respectively, as discussed above, is presented in Figure 10. In addition to pre-drainage to reduce SGE, additional actions that may be taken by the mine operator to reduce the gas concentration in the ventilation air include (a) increase the ventilation air quantity, (b) reduce the production rate, and (c) drain gas from the goaf to reduce the gas volume that would otherwise report to the ventilation system. Reducing production rate is generally not desirable and there is typically limited capacity available within the mine ventilation system at most mines to support increasing the ventilation quantity supplied to the longwall panel. Therefore, most effective option available to mine operators to reduce gas emissions, in addition to more intensive use of pre-drainage, is to utilise efficient goaf gas drainage systems.

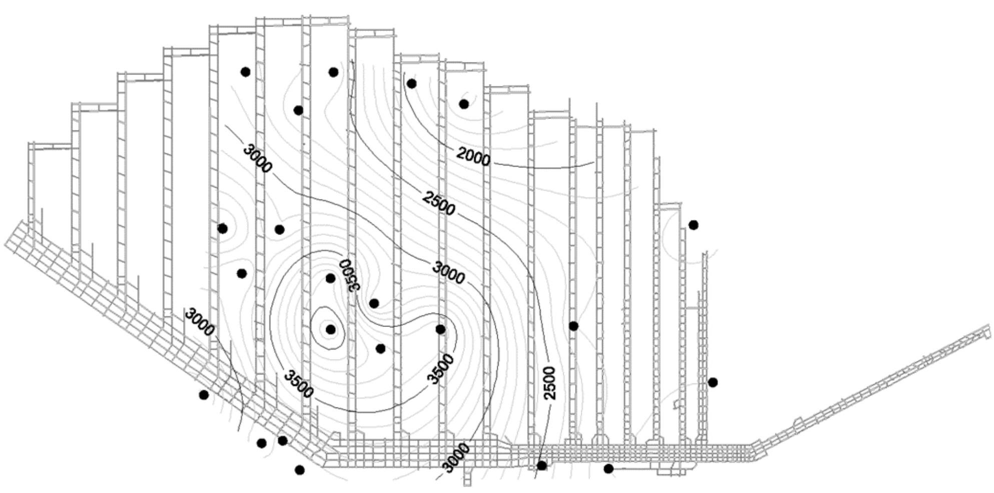

Figure 10: Average Longwall Gas Make (L/s) after pre-draining B seam to 4.0 m^3/t and D seam to 3.0 m^3/t

When designing systems to manage longwall gas emissions, the required capacity of the system should be based on expected 'peak' gas emissions. As the name suggests, the 'peak' gas emission rate is greater than the 'average' gas emission rate and tends to occur for relatively short periods before returning to the average rate characteristics for that specific mining area. The ratio of peak to average emissions will be confirmed through operating experience. However, in lieu of operating experience, designing the ventilation and gas management systems based on an emission rate of 1.5 x Average is considered reasonable.

In this example, 60 m^3/s of ventilation air is directed across the longwall face and exits the longwall panel via the tailgate roadway. If the target maximum gas concentration in the longwall return air is 1.0% CH_4 then the ventilation air has the capacity to dilute a maximum gas emission rate of 600 litres per second. Therefore, to maintain the gas concentration below the nominated maximum value of 1.0% CH_4, the mine will be required to provide and maintain goaf gas extraction systems that are designed to efficiently remove gas from the goaf such that the rate of gas emission into the ventilation system does not exceed 600 litres per second.

Figure 11 shows contours of the goaf gas extraction rate (litres per second) required to control goaf gas emissions to support longwall production at a rate of 1,000 tonnes per hour whilst maintaining the return airway gas concentration at 1.0% CH_4, based on a peak-to-average gas emission ratio of 1.5 and having pre-drained the B seam to 4.0 m^3/t and the D seam to 3.0 m^3/t prior to longwall extraction.

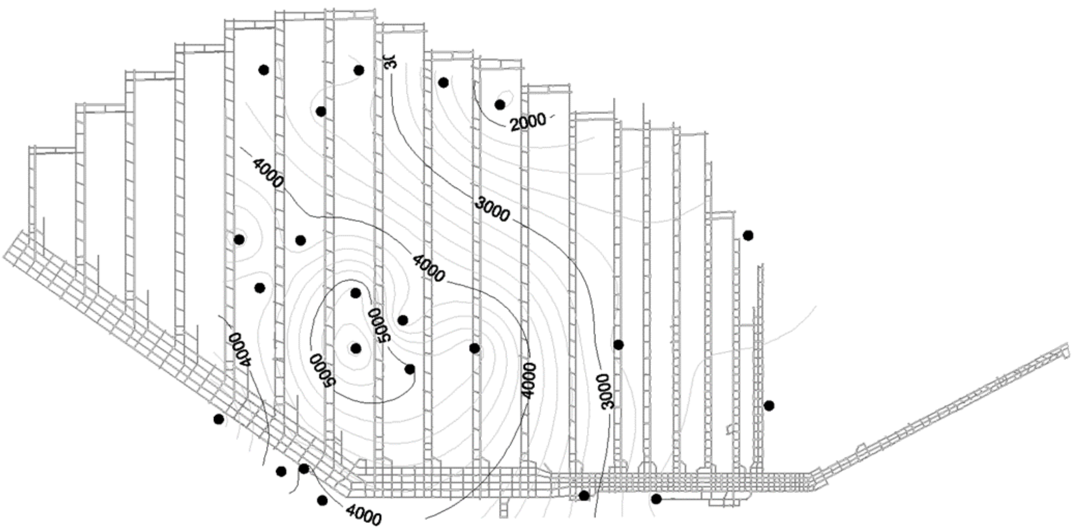

Figure 11: Goaf drainage rate (L/s) to maintain TG gas to 1.0% CH_4 (Peak) – B seam drained to 4.0 m^3/t and D seam drained to 3.0 m^3/t.

Increased resolution can be achieved in the gas emission forecast through coupling the gas reservoir model and the mine production schedule. Provided there are sufficient exploration boreholes to provide confidence in the resolution and accuracy of the gas reservoir model, coupling the gas reservoir model with the production schedule will provide a forecast of gas emissions corresponding to the variable production rates presented in mine production schedules. The effect on gas emissions and gas concentrations resulting from varying the pre-drainage and goaf drainage intensity in various parts of the mine that align with specific periods in the production schedule may also be investigated.

The coupled model produces a forecast of future gas emissions that may be used to identify periods of high gas emission where general body methane concentration is expected to exceed statutory limits. In addition to modelling and assessing the impact of varying pre-drainage on reducing SGE, the coupled model is also used to assess the impact of varying the rate of gas extraction from the goaf

(goaf drainage) to further reduce total longwall gas emission into the ventilation air and the resulting impact on general body methane gas concentration in the ventilation air.

Goaf Drainage

Similar to pre-drainage, the extraction of gas from the goaf, commonly referred to as goaf drainage, may be achieved through drilling boreholes from both surface and underground drilling sites. Given the larger capacity of surface drilling rigs, boreholes drilled from the surface tend to be larger diameter and support greater gas extraction rates. Some Australian underground coal mines operate goaf drainage systems that consistently extract greater than 9,000 litres per second of CH_4 from the goaf to support longwall production rates of 8.0 to 9.0 Mtpa.

Drilling large boreholes, typically minimum diameter of 10 inch, in advance of the retreating longwall panel, at a spacing that may vary between 50 metres to 200 metres along the length of the longwall panel and typically offset 30 to 40 metres from the tailgate pillar, is the most common method used for goaf drainage in Australian underground coal mines (Black and Aziz, 2009). An alternative surface-based drilling method trialled at several Australian mines, utilises medium-radius drilling (MRD) directional drilling technology to drill one or more long laterals into the strata above the longwall block (Black and Aziz, 2009).

In areas where surface access is restricted, UIS drilling may be used to support or replace surface-based drilling and gas extraction. The smaller diameter of UIS boreholes does limit gas extraction through each borehole therefore, to increase total goaf gas extraction, an increased number of boreholes is required, and if conditions allow, the boreholes may be reamed to a larger diameter.

Gas extraction through goaf seals is also an option however due to the tendency for air to be drawn around the perimeter of the active longwall goaf, goaf drainage through longwall seals typically draws low purity gas.

GAS MANAGEMENT AND FUGITIVE EMISSION REDUCTION

Effective gas management and reduction of fugitive emissions from coal mines relies on quality technical investigation to identify and assess the significance of all potential sources of gas emission associated with the mine operations and to design effective systems to control and reduce emissions. Management commitment is crucial to achieving effective gas management and the reduction of fugitive emissions. Corporate policies and standards should clearly state the goals and objectives, and the commitment to achieving the stated goals and objectives should be reinforced through setting measurable performance targets for executive and management personnel at all levels within the organisation. Companies must also demonstrate their commitment by providing funds necessary to achieve the stated performance targets. Coal mine gas management and ventilation systems should be designed and managed to ensure the gas concentration limits specified in coal mine health and safety legislations are not exceeded and visible commitment to reducing fugitive emissions should be demonstrated.

In addition to the use of gas drainage to reduce gas emissions contaminating the mine ventilation system, maintaining high standards throughout the mine ventilation network will have a significant impact on reducing gas emissions into the mine ventilation air. For example, regular monitoring and inspections of mine seals installed to isolate mined areas from current workings, should include gas testing and visual inspection to identify any evidence of gas leakage and if identified, prompt action should be taken to stop any identified leaks.

Installing equipment on the surface of an underground coal mine to flare drained gas has a significant impact on reducing fugitive emissions. Drained gas may also be used as a fuel source for reciprocating engine driven power generation units.

CONCLUSION

To reduce the risk of high gas emissions that adversely affect mine production, thorough analysis of the gas reservoir, including detailed exploration and gas reservoir data collection, is required to quantify the volume of gas contained within the reservoir and the specific gas emission expected in each mining area. Incomplete exploration significantly increases the risk of underestimating the size of the gas reservoir that may lead to the gas drainage and fugitive emissions management systems being inadequate to support planned mine production.

In addition to providing a measure of gas emission from all potential sources impacted by coal extraction, gas reservoir modelling can be used to assess the impact of pre-drainage on specific gas emission. Coupling the gas reservoir model to the mine production schedule will produce a gas emission forecast that may be used to calculate the expected average and peak gas concentration in the ventilation air. If the gas emission forecast indicates periods where the gas concentration exceeds statutory limits, the impact of goaf drainage and additional pre-drainage to reduce both gas concentration in the ventilation air and fugitive gas emissions from the mine can be assessed.

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